分布型降雨流出モデルによる2004年10月台風23号由良川洪水の解析

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Analysis of the Yuragawa River Flood by Typhoon No. 23 in October 2004 Using a Distributed Rainfall-Runoff Model-

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Synopsis

This paper analyzes the Yuragawa river flood by Typhoon No. 23 on 19-22 October 2004 which brought the large number of casualties and loss of asset especially at the downstream region of the Yuragawa catchment. First, the discharge-hydrograph at Fukuchiyama during the flood is reproduced by a distributed rainfall-runoff model. The simulated discharge-hydrograph after the parameter adjustment shows a good fit with the observed discharge-hydrograph. Afterwards, the model with the same parameter is applied to two past-medium-size floods, which also exhibit the good performance of the model. From these applications, it is clarified that the physically-based distributed rainfall-runoff model has a high potential to reproduce floods of any size in the catchment.

Keywords: Distributed rainfall-runoff model, Yuragawa catchment, Typhoon No.23, 2004, Rader-AMeDAS rainfall

1. Introduction

Yuragawa river is a first class river located in Kyoto prefecture (see Fig. 1). The catchment size is 1880 km^2 and the channel length is 146 km. The total population of the cities and towns in the catchment area attains around 0.3 million. The topography along the upper reach of the river in the catchment exhibits typical landscape of mountain regions. Canyon and fluvial terrace are well developed, thus the slope is steep. There is Fukuchiyama Basin in the middle region of the riverine in the catchment. This is the only one basin in the catchment where the river width widens, and the slope becomes slightly mild. The lower reach of the riverine forms valley flood plain. The slope around the reach is mild but the river flows in the narrow valley. Thus, in total the region is considered water-disaster prone.

The climate belongs to Japan Sea climatic division. The annual rainfall ranges between approx. 1600-2100 mm, although, as a general trend, inland region has less rainfall. Strong rainfall is observed in rainy and typhoon seasons.

In October 2004, four cities and one town (Fukuchiyama, Maizuru, Ayabe, Miyazu cities and Ooemachi town) along the Yuragawa river was heavily damaged by Typhoon No. 23. The number of flooded houses was approx. 1700 and inundated area was around 2600 ha. At that time, two-day areal rainfall in the Fukuchiyma catchment reached around 276 mm. The second highest historical water-stage which is next to the one by Typhoon No. 13, 1953 (Flooded houses: approx. 3800) was observed at Fukuchiyama.

Currently, the so-called "urgent flood control measure" for the downstream region of the Yuragawa catchment is being taken by MLIT (Ministry of Land, Infrastructure and Transport). The target completion year is 2015. This measure includes the creation of flood hazard maps, the construction of ring levees and the execution of the safety exercise, etc. Reviewing these

Fig 1. Yuragawa catchment (MLIT, 2005)

situation, and for preparing the next possible large-scale floods, it is considered wise to construct a physically based distributed rainfall-runoff model capable of simulating the large scale flood events in this region. Note that, in Japan, a flood-control plan is made firstly by determining the design rainfall of a proper return period and then estimating the design flood discharge calculated by a rainfall-runoff model using the designed rainfall.

For instance, Takasao et al. (1983) and Takara et al. (1983) constructed a real-time flood runoff model based on a storage function model. However, any kinds of physically-based distributed rainfall-runoff models in Japan are not yet examined and validated well enough for these level floods.

2. Review of the past flood records

Table 1 indicates the past major flood records in Yuragawa catchment. The data therein is taken from the Improvement Plan for Yuragawa River (MLIT, 1997, 2003, 2004 a, b, 2005). In the table, the rainfall indicates the areal rainfall, while the water level and discharge are measured at Fukuchiyama observatory. Figs. 2 and 3 show the maximum discharge and water level extracted from the table, respectively.

Table 1. Major flood records of Yuragawa

Dominical year	Date	Factor	Total rainfall	Max water level	Max water discharge
[-]	[-]	[-]	[mm]	[m]	[m^3/s]
1953	Showa 28.9.25	Typ. No.13	360.2	7.8	6500
1959	Showa 34.9.26	Isewan Typ.	261.1	7.1	4384
1961	Showa 36.10.28	Typ. No.26	231.7	5.1	2402
1965	Showa 40.9.17	front	252.8	5.42	2833
1972	Showa 47.9.16	Typ. No.20	183.2	6.14	4063
1982	Showa 57.8.1	Typ. No.10	190.1	5.45	3636
1983	Showa 58.9.28	Typ. No.10	246.4	5.57	3608
1990	Heisei 2.9.20	Typ. No.19	251.6	4.64	2469
1995	Heisei 7.5.12	LP	245.5	4.23	2242
1998	Heisei 10.9.22	Typ. No.7	127	4.49	2178
1999	Heisei 11.6.30	rain front	121	4.57	2203
2004	Heisei 16.10.20	Typ. No.23	279	7.55	5297

From these figures, it is clarified that floods due to Typhoon No. 13 in 1953 and No. 23 in 2004 are extremely large (discharge: 6500, 5300 m^3/s; water stage: 7.8, 7.35 m, respectively). Focusing especially on the discharge, the years of 1959, 1972, 1982 and 1983 show the discharge of approx. 3500-4500 m^3/s, while other years exhibits the magnitude of 2000 m^3/s. Note that smaller scale floods occur almost every year.

Fig. 4 is for the impression of the current situation of the site. The picture shows the flood mark taken at the field investigation in 2004. This is the remains of a restaurant along the Route 173 near the town Ooemachi. There, the water level reached even the ceiling of the first floor of the restaurant.

Referring to the Improvement Plan for Yuragawa River, the design flood discharge is calculated based on the flood event in September 1953. In the report, the peak discharge is set up as 6500 m^3/s at Fukuchiyama. It is planned that 900 m^3/s of 6500 m^3/s is allocated to the flood control facilities in the catchment and the river channel receives the remaining 5600 m^3/s.

3. Distributed rainfall-runoff model

The topography of Yuragawa catchment is modeled using the geomorphologically-based hydrological modeling system (Geohymos). The physically based distributed rainfall-runoff model is constructed using the object-oriented hydrologic modeling system (Ohymos). The overview of the modeling systems is given in the following sections.

3.1. Topography modeling

The topography modeling of the catchment is carried out by adopting the digital expression of Shiiba et al. (1999). The basic procedure is as follows: (1) Dot sequence data of the riverine is formed by transforming Digital National Land Information (DNLI includes Riverine position file: KS-272 and Riverine unit cactchment book: KS-271). (2) The coordinate of each dot sequence data is modified such that each dot moves on to the nearest node of the element defined in Digital Elevation Map (DEM) by Geographical Survey Institute. The resolution of DEM is currently either 50 m or 250 m. (3) Using the elevations of the nodes, the slope element attached to each river segment and the flow direction on the element is determined in one-dimensional manner.

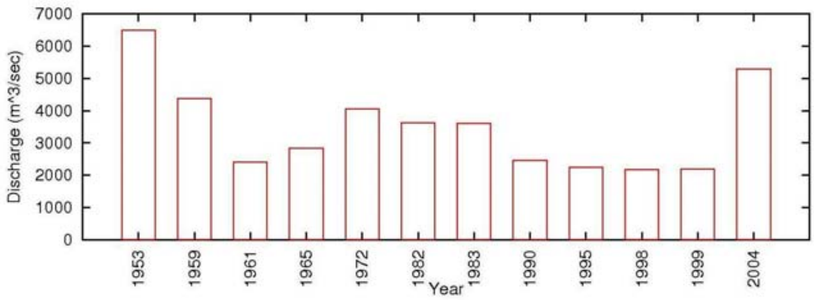

Fig. 2. Max discharges of the major floods at Fukuchiyama observatory in Yuragawa catchment

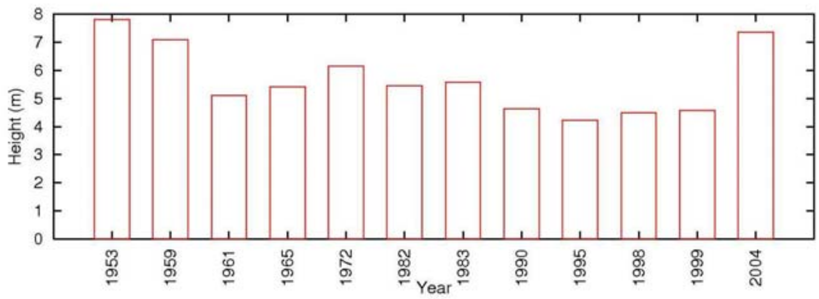

Fig. 3. Max water level of the major floods at Fukuchiyama observatory in Yuragawa catchment

Fig.4. A flooded restaurant as of 2004 in Ooemachi city.

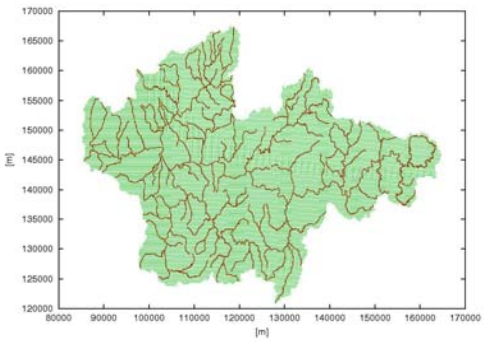

Fig. 5. Yuragawa catchmet (shaded area) and the river channel network (red solid line).

In the following application, 250 m resolution is selected for the construction of the topography to reduce the CPU time. The modeled catchment is shown in Fig. 5. Note that, in the figure, the coordinate system follows UTM system. The origin of the coordinate system is taken where (north latitude, east longitude) = (34^o, 134^o) is transformed to the coordinate in the UTM system. As the result, the catchment area by the model becomes 1866 km^2 (nominal: 1880 km^2).

3.2. Distributed rainfall-runoff model

The rainfall-runoff simulation is carried out by a distributed rainfall-runoff model constructed by Ohymos which is developed by Ichikawa et al. (2001). The governing equations both for the flow over the slope (hereinafter: slope flow) and in the channel (hereinafter: channel flow) are derived based on the kinamatic wave theory (e.g. JSCE, 2001).

3.2.1. Slope flow

The governing equation for the slope flow is expressed as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r(t) \tag{1}$$

where t is the time, x the distance from the top edge of

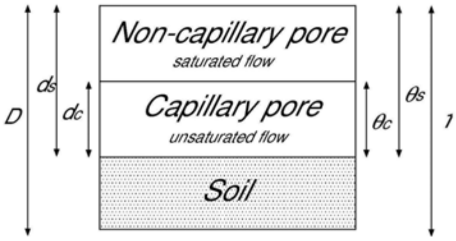

Fig. 6. Schematic diagram for the stage-discharge relation (Tachikawa et al., 2004).

the slope, h the water level on the slope, q the discharge per unit width. Regarding the estimation of the discharge per unit width, the stage-discharge relation by Tachikawa et al. (2004) is used.

In the relation (see Fig. 6), the flow regime changes according to the flow depth in the subsurface soil layer. First of all, the relation distinguishes three flow regimes: (1) the capillary flow through the capillary zone ($0 \leqq h \leqq d_c$), (2) the gravity flow in the large pore ($d_c < h \leqq d_s$) and (3) the subsurface flow ($d_s < h$). Then, the flow velocity for each regime is calculated using the governing equations for the regime. Accordingly, the discharge per unit width is estimated from the flow velocity.

To be more precise, the discharge per unit width is calculated as follows:

$$q(h)=\begin{cases} v_c d_c\left(\dfrac{h}{d_c}\right)^{\beta}, & (0 \le h \le d_c) \\ v_c d_c + v_a(h-d_c), & (d_c, < h \le d_s) \\ v_c d_c + v_a(h-d_c)+\alpha(h-d_s)^m, & (d_s < h) \end{cases} \tag{2}$$

where $v_c = k_c i$, $v_a = k_a i$, $\alpha=\sqrt{i}/n$. Here v_c is the capillary flow velocity, k_c the permeabiltiy in the capillary zone, i the slope gradient, v_a the gravity flow velocity in the large pore, k_a the permeability in the large pore and n the manning's coefficient. Note that $\beta k_c = k_a$ is fulfilled to satisfy the continuity condition of the discharge. β takes normally the value of around 2-6. In the numerical simulation, the propagation velocity $c=\partial q/\partial h$ is calculated from the discharge per unit width. Transforming the continuity equation (1) yields:

$$\frac{\partial q}{\partial t}+c\frac{\partial q}{\partial x}=cr(t) \tag{3}$$

This system of equations is solved using a finite difference method. The model parameters for this formulation are the equivalent layer thickness expressing the effect of the entire pore d_s, of the capillary zone d_c, roughness coefficient n and the permeability for the large pore k_a, and the ratio of the permeability for the large pore to the capillary zone β.

3.2.2. River channel flow

The kinematic wave theory is used for the routing of the river channel flow. The governing equation is expressed as:

$$\frac{\partial W}{\partial t}+\frac{\partial Q}{\partial x}=q(t) \tag{4}$$

where W is the cross sectional area of the channel, Q the discharge in the channel and q the discharge per unit width from the slope element. Provided that the stage-discharge relation in the channel follows the manning's law, we get:

$$Q=\frac{1}{n}WR^{\frac{2}{3}}I^{\frac{1}{2}} \tag{5}$$

where n the roughness coefficient in the channel, R the hydraulic radius and I the channel slope. The hydraulic radius R is expressed using two constants K_1 and Z such that:

$$R=K_1W^z \tag{6}$$

Substituting Equation (6) into (5) yields

$$Q=\frac{K_1^{\frac{2}{3}}I^{\frac{1}{2}}}{n}W^{(1+\frac{2}{3}Z)} \tag{7}$$

K_1 and Z are estimated from the configuration of the channel cross section. Q is calculated using the channel slope I and roughness coefficient n. A finite difference method is used for solving the system of equations.

4. Simulation condition and result

Using the above mentioned model, the rainfall-runoff simulation is carried out for the period of October 16 to 21, 2004 when the Typhoon No. 23 passed through. Rader-AMeDAS precipitation data (temporal resolution is 1 hour and spatial resolution is approx. 2.8 km) published by the Japan Meteorological Business Support Center is used as the input rainfall. Fig. 7 shows where Rader-AMeDAS data is given (dots). Fig. 8 shows the time series of the areal rainfall in the Fukuchiyama catchment. This areal rainfall is calculated from the Rader-AMeDAS data (see Fig. 1 for the location of Fukuchiyma observatory).

Table 2. Flood data for the evaluation of the model

Flood	Flood term	Max discharge
Event 1	2004/10/19 0:00 - 10/21 23:00	5271.2 m^3/s
Event 2	1998/10/16 0:00 - 10/19 6:00	1675.1 m^3/s
Event 3	1999/6/28 0:00 - 6/30 23:00	2203.0 m^3/s

Table 3. Determined model parameter

n	k_s	d_c	d_s	β
[$m^{(-1/3)}s$]	[m^3/s]	[m]	[m]	[-]
0.2	0.001	0.275	0.375	4

The observed discharge is estimated by transforming the observed water level at Fukuchiyama observatory using the H-Q relationship. This is shown in Fig. 8 below (solid line). The discharge hydrograph at Fukuchiyma simulated by the distributed rainfall-runoff model is also shown in Fig. 8. Note that the ultimate model parameters for the simulation are determined by simple trial and error method and these are listed up in Table 3. Moreover, to quantify the goodness of fit between the simulated and observed hydrographs, Table 4 shows the Nash-Sutcliffe index, the difference of the peak discharge (PE) between the simulation and observation, the ratio of PE to the observed discharge (RPE), and the time difference of the peak discharges (TE). Note that the Nash-Sutcliffe index and the RPE are calculated as follows:

$$\mathrm{NS}=1-\frac{\sum(Q_0-Q_s)^2}{\sum(Q_0-\overline{Q_0})^2} \tag{8}$$

$$\mathrm{RPE}=\frac{Q_0^{\max}-Q_s^{\max}}{Q_0^{\max}} \tag{9}$$

where Q_o and Q_S are observed and simulated discharges per hour, $\overline{Q_0}$ the time averaged observed discharge, Q_o^{max}, Q_S^{max} are the max values of the observed and simulated discharges respectively.

It is apparent from these results that the distributed rainfall-runoff model can in gross simulate appropriately the large scale flood event such as the event by Typhoon No. 23 in 2004. Specifically PE and RPE in Table 4 exhibits pretty high level fitness. The Nash-Sutcliffe index shows also good fit. As an overall trend, the initial rising of the simulated hydrograph is delayed compared with the observed one, while the recession of the simulation occurs slightly earlier than that of the observation. It is considered that these differences can be reduced by the further adjustment of the parameters d_s, d_c, and k in the stage-discharge relationship. Note that these parameters influence the retention and movement of the rainwater in the soil. Parameter identification problems are classic but yet new and to be investigated in details using any optimization theory.

Then, it is investigated if such calibrated model capable of simulating the large scale flood event can also reproduce the past small to medium scale flood events in the region appropriately. Here, two flood events having occurred for the periods of October 16-19, 1998 (see Event 2 in Table 2; max discharge: 1675.1 m^3/s) and of June 28-30, 1999 (see Event 3 in Table 2; max discharge: 2203.0 m^3/s) are selected for the verification. The scales of these floods are, in terms of the peak discharge, one third and half of the 2004 flood.

The observed discharge curves (solid line) for the Event 2 and Event 3 are shown in Figs. 11 and 12 respectively. The observed discharge is transformed from the observed water level using the H-Q relation. Rader-AMeDAS data (temporal resolution: 1 hour; spatial resolution: 5.5 km) is used as the input rainfall information for the model. Figs. 11 and 12 above show the areal rainfall in Fukuchiyama catchment calculated from the Rader-AMeDAS data. Under these conditions and using the same parameter set, the discharge hydrographs are simulated. Figs. 11 and 12 below show the results (broken line). The indices expressing the

Table 4: Indices for the evaluation of goodness of fit between the simulation and observation.

Flood	NS index	PE [m3/s] (RPE [%])	TE [min]
Event 1	0.877	2.3 (0.043)	44.3
Event 2	0.925	92.9 (5.5)	148
Event 3	0.889	179.3 (8.1)	51.3

NS: Nash-Sutcliffe index; PE (m^3/s): peak discharge error; RPE (%): relative peak discharge error; TE (min): timing error where negative value indicates that the peak discharge simulated comes earlier than the one observed.

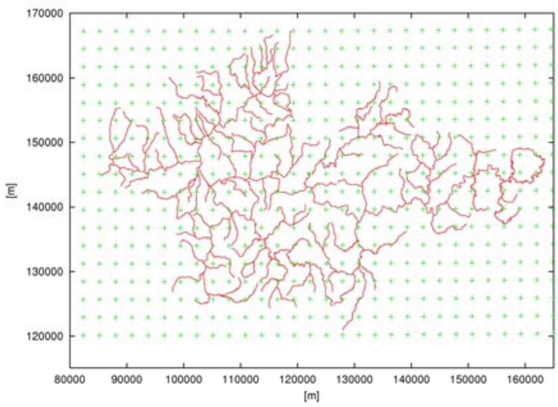

Fig. 7. Yuragawa river channel network (solid line) and Rader-AMeDAS nodes (green dots) for Event 1

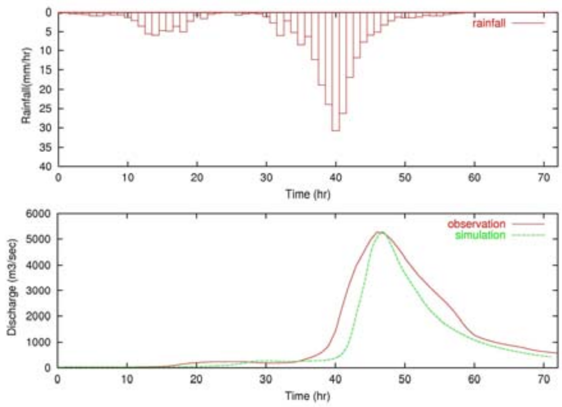

Fig. 8. Areal rainfall in the Fukuchiyma catchment for Event 1 (above); Simulated and observed discharge hydrographs at Fukuchiyama for Event 1 (below).

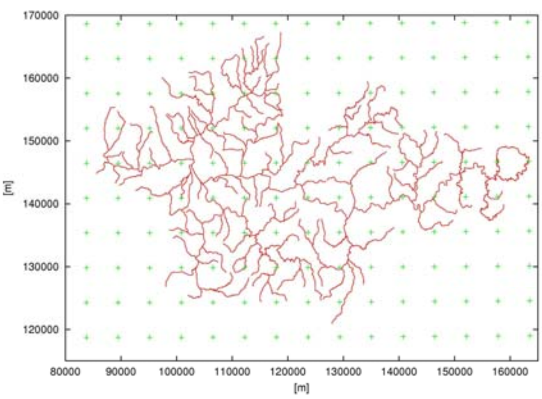

Fig. 10. Yuragawa river channel network (solid line) and Rader-AMeDAS nodes (green dots) for Event 2 and 3.

goodness of fit between the simulated and observed hydrographs are listed up in Table 4.

As indicated in the table, Nash-Sutcliff indices both for Event 2 and Event 3 are around 0.9. In other words, the model can simulate in gross appropriately the small

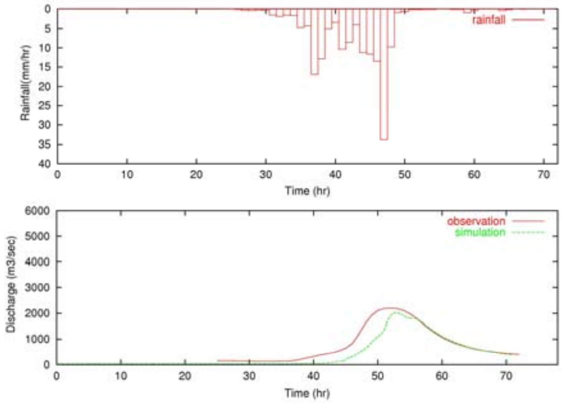

Fig. 11. Areal rainfall in Fukuchiyma catchment (above) for Event 2; Simulated and observed discharge hydrograph at Fukuchiyama observatory for Event 2 (below).

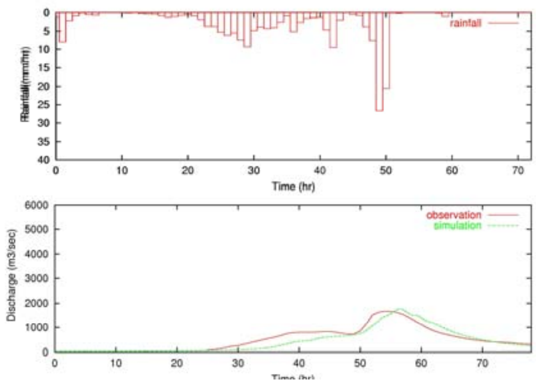

Fig. 12. Areal rainfall in Fukuchiyma catchment (above) for Event 2; Simulated and observed discharge hydrograph at Fukuchiyama observatory for Event 2 (below).

to medium size floods as well. Considering PE and RPE, although the accuracy somewhat drops down compared with Event 1, yet the fitness is considered well enough. As a whole, the rising parts of the simulated hydrographs for both cases are delayed as observed in Event 1. The reasons may fall in the overestimation of the rainwater retention effect in the soil due to the mismatch of the parameters, the underestimation of the observed rainfall or the insufficient H-Q relationship.

Although this aspect still needs to be investigated in details, it can be concluded that totally the model was able to simulate not only the large scale flood event equivalent to the design flood but also the small to medium scale flood events with the same parameter set.

5. Conclusion

As examined so far, the distributed rainfall-runoff model was able to simulate small, medium to large scale flood events in Yuragawa catchment. One reason why the good fitness is obtained is probably that the model can incorporate the spatial information of the topography as well as the spatial temporal information of the rainfall pattern and the stage-discharge relation can consider different flow regimes in the soil. As the past researches (Tachikawa et al. (2004), Takara et al. (2004) and Sayama et al. (2005)) showed that the model parameters are different according to the modeled catchment, the establishment of the systematic parameter identification methodology is expected as the future work.

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分布型降雨流出モデルによる２００４年１０月台風２３号由良川洪水の解析

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要旨

2004年（平成16年）10月20日に，大阪市付近に上陸した台風23号により由良川沿川の四市一町（福知山市・舞鶴市・綾部市・宮津市・大江町）は，浸水家屋約1700戸，浸水面積2600haに達する大きな被害を受けた。この台風23号は福知山上流域で流域平均2日雨量276㎜の降雨をもたらし，福知山水位観測所では，昭和28年に福知山市内で浸水家屋数約3800戸に達する大災害をもたらした台風13号に次ぐ水位が観測された。本研究では，こうした大規模洪水が物理的な背景にもとづいた分布型降雨流出モデルで適切に再現できるかを検討している。ここではまず2004年洪水を分布型流出モデルにより再現した。次に，2004年洪水を再現可能なモデルが過去の小中規模洪水を適切に再現するかを検討した。その結果、同じモデルパラメータの値を用いて，同地域においては中小洪水から計画規模に匹敵するような大洪水まで概ね良好に再現できることがわかった。

キーワード：分布型流出モデル，由良川流域，2004年台風23号，レーダー・アメダス雨量